ASTA Machine Protection System

(Arden Warner, August 20th, 2012)

Introduction

The beam at Fermilab's ASTA facility, when operational, will need systems to protect critical components from beam induced damages such as beam pipe collision and excessive beam losses. The accelerator is being designed with the capability to operate with up to 3000 bunches per macro-pulse, 5Hz repetition rate and 1.5 GeV beam energy. It will be able to sustain an average beam power of 72 KW at the bunch charge of 3.2 nC. Operation at full intensity will deposit enough energy in niobium material to approach the melting point of 2500 °C. In the early phase with only 3 cryomodules installed the facility will be capable of generating electron beam energies of 810 MeV and an average beam power that approaches 40 KW. In either case a robust Machine Protection System (MPS) is required to mitigate effects due to such large damage potentials. The MPS must identify hazardous conditions and then take the appropriate action before damage is caused. Since the loss of a full bunch train can result in significant damage, the MPS must also be able to interrupt the beam within a macro-pulse and keep the number of bunches below the damage potential once the protection system reacts; the goal is to keep the number of bunches on the order of 3-6 bunches. With the high possible bunch frequency of 3 MHz this necessitates a reaction time in the range of 1-2 µs with cable delay included for the 134 metre long machine. The MPS will use the status of critical sub-systems and losses measured by a fast Beam Loss Monitor (BLM) system, using scintillators and photomultiplier tubes (PMT) to identify potential faults. Once a fault is observed, the MPS can then stop or reduce beam intensity by removing the permit from different beam actuators.

MPS Concept

From a machine protection point of view, the dump locations describe the final destination of the beam that traverses a path along the beam-line. These paths are termed operation modes and are validated by the MPS before the beam permit is released. The MPS validates these paths by monitoring all critical devices and diagnostics along the path and ensuring that they are all in good status and ready to receive beam at the requested intensity. The machine will also be capable of operating over a wide range of beam parameters as long as the total beam power remains below the limit of the beam dump capability and satisfies radiation shielding requirements. For machine protection purposes several beam modes have been defined; the beam mode sets limits on the number of bunches and therefore the intensity. Initially the following two modes will be active in the system:

- Low intensity mode – which allows the minimal beam intensity needed for OTR/YAG diagnostics. This is below the threshold potential for beam induced damage. In this mode there is no fast reaction to beam loss within a bunch train.

- High intensity mode – which does not impose a limit on the number of bunches, but enables fast intra-train protection by the MPS.

MPS Over-view

The simplified block diagram of the proposed MPS is shown in Figure 1. The system is divided into three functional layers which has connections to several external devices and sub-systems. The top layer (shown on left) comprises signal providers such as fast beam loss monitors, RF signals, quench protection, toroid transmission, vacuum, magnet power supplies and more. All devices in this category send status information to the MPS logic layer (permit system). Only simple digital signals (e.g. on-off, OK-not OK) are transmitted. All devices or subsystems that are determined to be pertinent to protecting the machine or necessary for machine configuration are included here. The state of the machine is determined from this comprehensive overview of the inputs and allowable operation modes are determined based on this information by the middle logic layer.

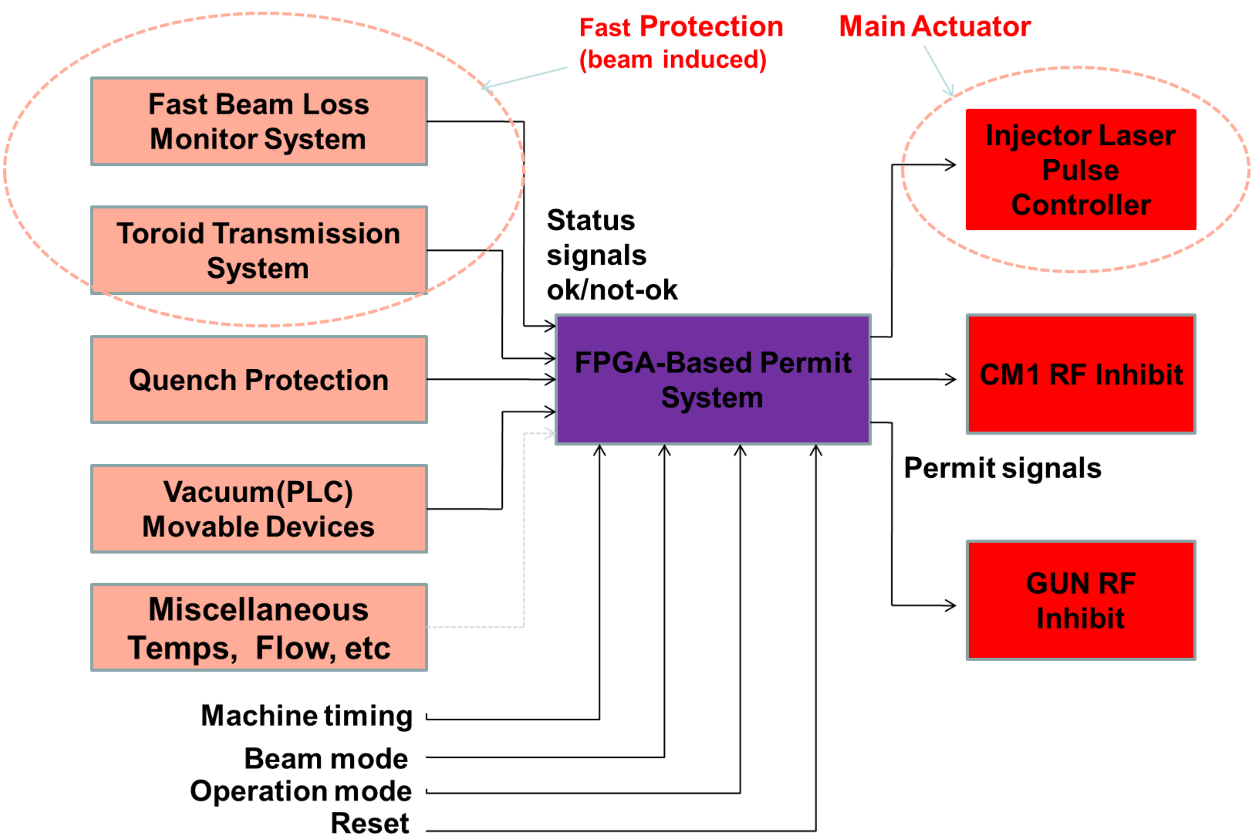

Figure 1. MPS Block Diagram

The main goals for the MPS system as a whole are:

- Provide precise protection of all critical components by first determining the fault severity (high, intermediate, etc.) and then taking the appropriate action to avoid damage.
- Allow for high availability by ensuring that the maximum requested beam intensity is allowed for the detected fault severity.
- Monitor MPS components and perform periodic self-checks in order to ensure robustness and a high level of reliability.
- Provide well-integrated, user-friendly tools for fault visualization, control and post-mortem analysis.

The permit system part of the MPS is capable of handling events on all time scales relevant to the machine. This layer is FPGA based and is thus fully programmable and handles complex logic tasks. The logic here will be designed to ensure safe operating conditions by monitoring the status of critical devices and by imposing limits on the beam power. It prohibits beam production or reduces the beam intensity by disabling the gun RF and the injector laser unless the requirements for the specific predefined modes are fulfilled when that mode is requested. The final layer of the system shows the main actuators. This comprises all of the points where the MPS logic may act on the operation of the machine and prevent beam from being produced or transported; the main actuator being the injector laser. When any of the non- masked inputs signal an alarm status the MPS permit system (logic layer) can do one of several things based on the severity of the fault: i.e. switch off the injector laser to suppress the production of new bunches, reduce the intensity by dialling back the number of bunches, or inhibit the RF power from the first cryomodule (CM1) as a precaution against transport of dark current from the RF gun.

Laser Pulse Controller

One of the main actuators for the MPS is the injector laser pulse control system shown in figure 2. This will be the device that controls the number and the spacing of bunches in a macro-pulse by picking single laser pulses out of a train. This is achieved by manipulating the Pockels cell (voltage-controlled wave plates). This system is also the main actuator for beam inhibits issued by the MPS. It is a VME based board with a fully programmable FPGA. It has inputs for the requested beam modes defined by the logic layer of the MPS, the MPS permit signal, the 3 MHz machine timing, and for a macro-pulse trigger. Based on the laser/gun design, it would have control outputs for the Pockels cell driver, a mechanical shutter and a first bunch timing signal. From the protection system point of view the pulse controller is used to:

- Block the Pockels cell based pulse kickers as long as **any** MPS input is in an alarm state.

- Enforce the limit on the number of bunches as given by the currently selected beam mode.
- Close the laser shutter on request of the MPS. This may happen when there is no valid operation mode or when some combination of loss monitors exceed thresholds which trigger a dump condition.

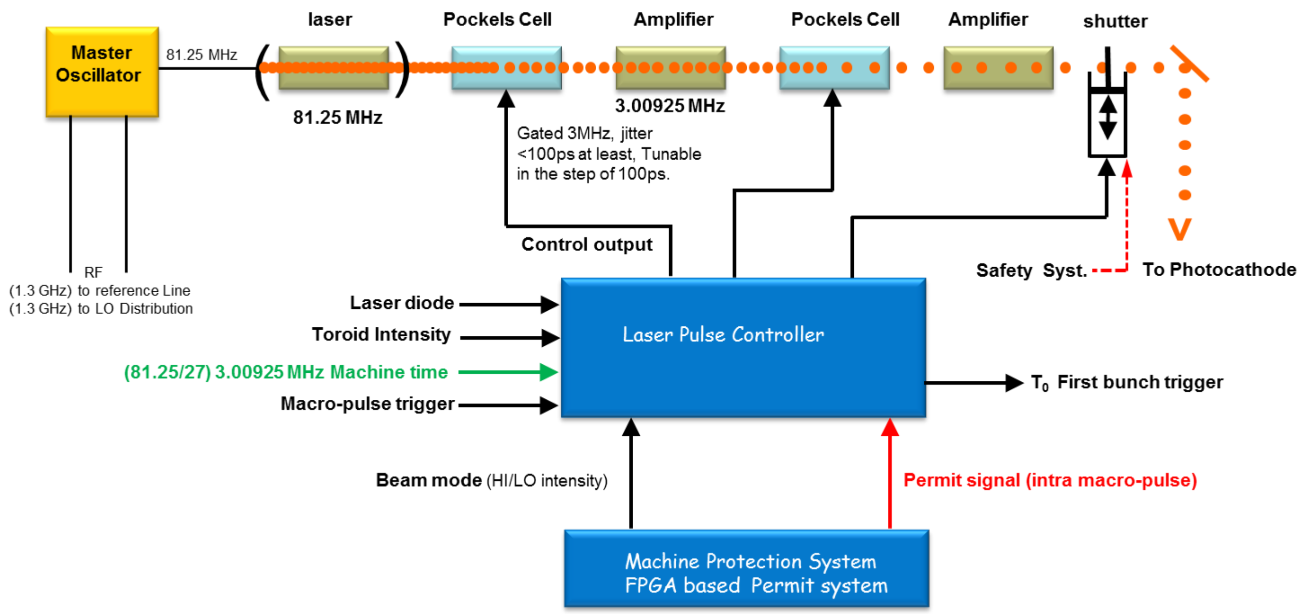

Figure 2. Laser pulse controller system

Fast Beam Loss Monitors

ASTA will use about 40 beam loss monitors for diagnostics and machine protection. A fast protection scheme associated with these monitors will be designed to interrupt the beam within a macro-pulse and will rely heavily on the ability to detect and react to losses within a few nanoseconds. The monitors are made of plastic scintillator with photomultipliers (PMTs) attached and have been built and tested. The BLMs will serve the dual purpose as an accelerator diagnostic for tuning and as the primary detector for the fast machine protection system. The monitors will deliver a measurement of beam and dark current losses to the control system as well as generate a fast alarm signal when the beam losses exceed user-defined thresholds. The time resolution of the loss measurement will also provide the ability to distinguish single bunches within each macro pulse. This requires a sampling frequency of at least 3 MHz (the bunching frequency of the machine) with a repetition rate of 5 Hz. The alarm output is a critical component for machine protection. The desire is to provide a machine protection trip well before the beam can damage accelerator components. If one of the programmed thresholds is exceeded or if an error condition such as a high voltage failure or failed monitor is detected the system should report this to the MPS logic which in turn reduces the intensity or inhibits the beam. The main requirements for the BLM system are:

- Provide both machine protection and diagnostic functions.
- Instantaneous read-back of beam loss.
- Digital output for integrating and logarithmic signal (12 bit)
- Built in self-test and on-board signal injection for testing of monitors between pulses.
- FPGA controlled.
- Local data buffer.
- VME interface to ACNET control system.
- Continuous and pulsed monitoring.
- Wide dynamic range.

Loss Monitor Design and Specifications

The loss monitors are made from a Y-shaped plastic scintillator (EJ-208) with a very gain stable photomultiplier. The PMT type was selected for high linearity and excellent gain stability (typically less than 5% drift in the first 24 hours after power on). The unit includes a low-power embedded high voltage divider with a typical HV supply current of 15µA at 1000 volts. The embedded high-voltage divider employs a transistorized voltage divider for best linearity at the lowest power consumption. It supports high anode currents (I > 100 µA). A fast green LED is embedded within the plastic. All units are housed in a steel magnetic shield made of 0.5 mm thick µ-metal. See figure 3.

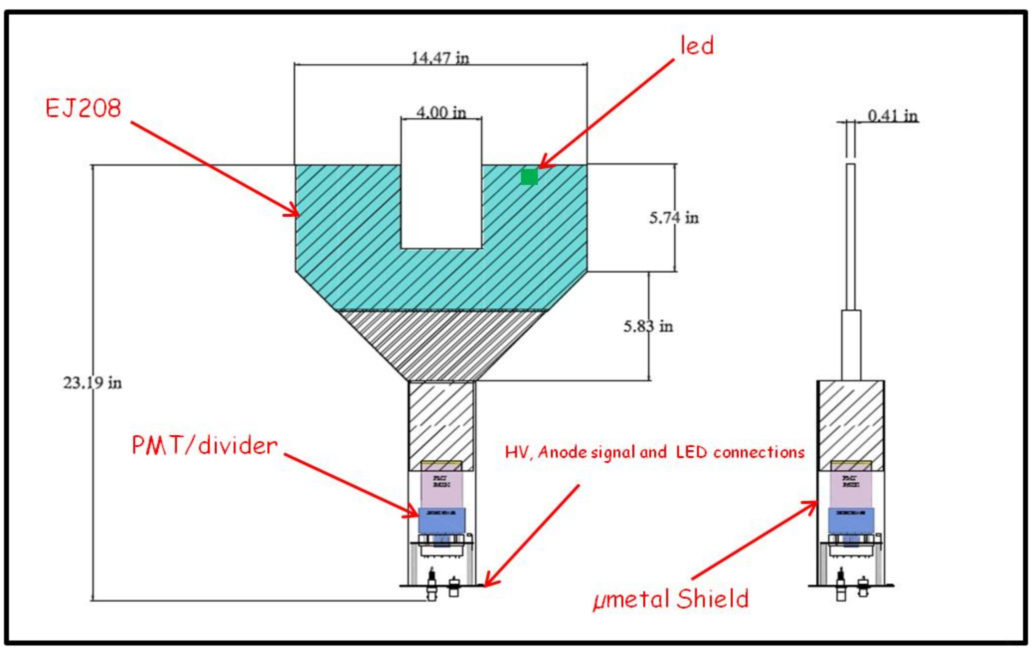

Figure 3. Beam loss monitor

The embedded LED in the plastic provides an operability check of each monitor. An LED driver will initiate a test pulse shortly before or after each RF pulse at the machine repetition rate of 5 Hz. The amplitude of the test pulse will be adjustable. To ensure that the PMTs are connected and functioning properly; the high voltage of each PMT or its current consumption will be monitored. All loss monitors are individually powered. Table 1 is a list of monitor characteristics.

Theory of operation

The PMT is powered using negative high voltage, and the anode is DC-coupled to its BNC connector. The last dynode is sent to its BNC connector via a 100Ω resistor and a 1 nF capacitor. The DC anode current of the PMT can be related to the dose rate deposited in the plastic scintillator as follows:

$$I = S_P * m * \dot{D}$$

Where S_p is the energy calibration, expressed in pC/MeV for convenience when measuring energy spectra, or C/J for dosimetry. Note, 1pC/MeV correspond to 6.24 C/J. The mass of the plastic scintillator $m \approx 0.380\ kg$, and $\dot{D}$ is the dose rate caused by the radiation field. Note that 1 Rad/hr = 2.78E-6 J/(kg s). The anode will support currents up to 50µA DC with minimal gain shift, < 2%. Hence the maximum dose rate or full scale range can be computed as

$$\dot{D} = I_{max}/(S_P * m)$$

And the dose range can be adjusted via the PMT gain and high voltage setting.

Parameter	Symbol	Min	Typ.	Max	Comment
Performance					
Energy resolution at 478 keV			70%		Cs-137 Compton corner
PMT gain			213 k		HV = 1000 V
PMT gain exponent			5.68		HV = 750 to 1200 V
Scintillator brightness			76 p.e/MeV		
Detector sensitivity	$\mathbf{S_p}$		7.0 pC/MeV		HV = 1200 V
			43.7 C/J		HV = 1200 V
Dose rate sensitivity	$\mathbf{S_d}$		46µA/(R/hr)		HV = 1200 V
Max dose rate (I = 50µA)	D_{max}		1.09 R/hr		HV = 1200 V
Detector sensitivity	$\mathbf{S_p}$		0.30 pC/MeV		HV = 700 V
			1.88 C/J		HV = 700 V
Dose rate sensitivity	S_p		1.98µA/(R/hr)		HV = 700 V
Max dose rate (I = 50µA)	$\mathbf{D_{max}}$		25 R/hr		HV = 700 V
LED					
Type			IF-E93, green,		

			fast LED		
Forward voltage			3.5 V		IF = 5 mA
Ballast resistor	RB		1.0 kΩ		
HV- subsystem					
HV range	HV	700 V		1400 V	Negative HV
HV supply current	I_{HV}		15µA	18µA	HV = 1000 V
Anode resistor to GND	R_A		100 kΩ		
Environmental					
Operating temperature	5° C			60° C	

Beam Loss Monitor Test Results

The beam loss monitor prototype was tested with electron beam at the A0 photo-injector lab. Since the front end to the test machine at ASTA will be similar the result should be reasonably representative; the signals were recorded with a scope. Figure 3 shows the result with 40 bunches with about 250 pC per bunch. The broadening in the signal was due to the inconveniently long (310 ft) RG58 cable used during the test. It is expected that the widths would be ~ 10-20 ns even with the appropriate length of cable. The PMT voltage used during the measurement was ~ 700 volts. The dark current background in this case was very small but some measure of dark current will be anticipated and considered in the system design. Figure 4 shows a case where a measureable amount of dark current was produced at the gun along with 10 bunches.

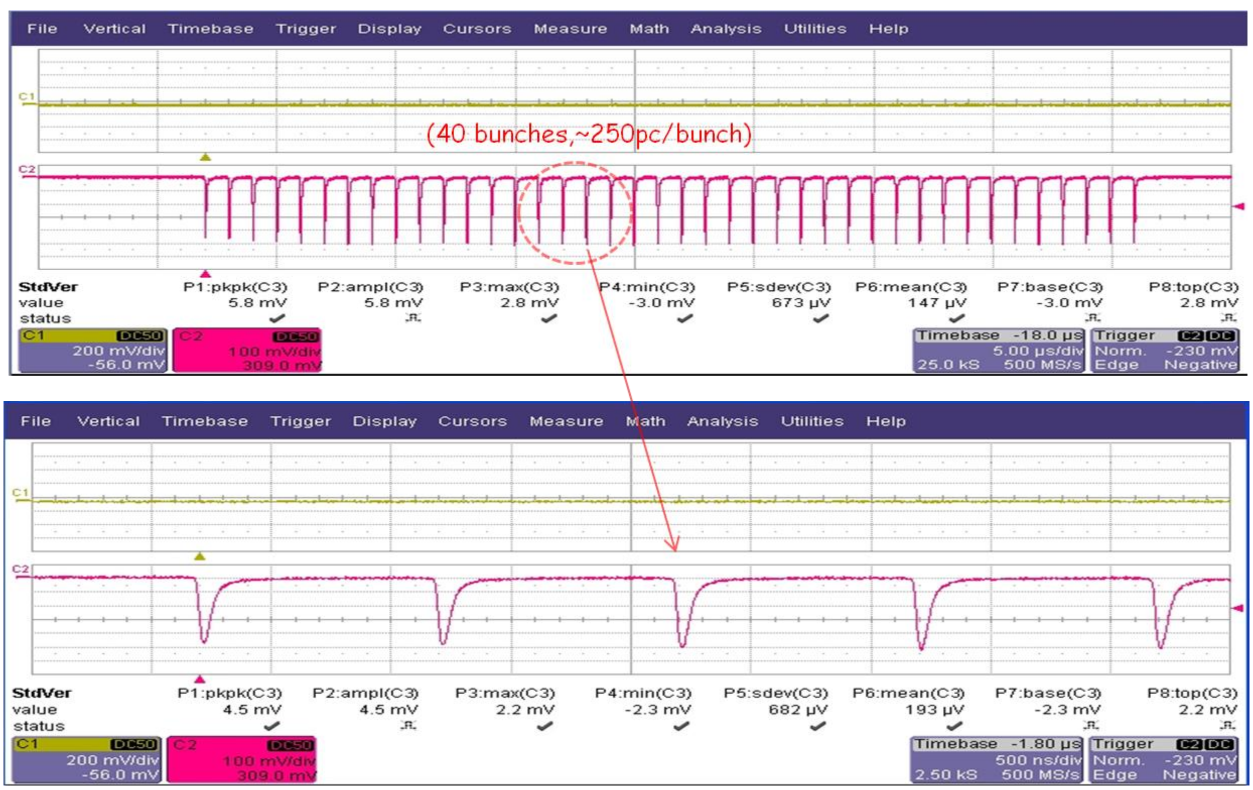

Figure 4. Signal from 40 bunches, 250 pC/bunch

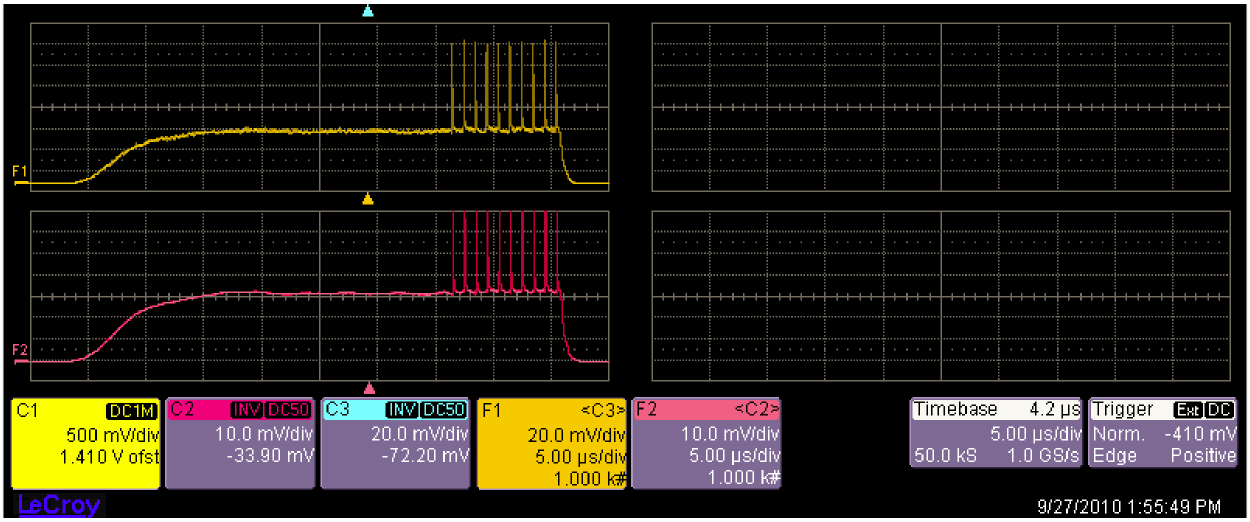

Figure 5. 10 bunches riding on dark current background

Beam Loss Monitor Signal Processing

The BLM signals will be continuously digitized with the full bunch frequency of the machine (3 MHz). Immediately after each sample "S" is available from the ADC, it is to be compared to a "single bunch" and a "multi-bunch" threshold T_s and T_m . An alarm will be signaled directly if $S > T_s$ or if $S > T_m$, a counter C incremented, and an alarm raised if C exceeds a configurable threshold T_c . The counter C will reset to zero between the macro-pulse. In a time window of ~ 1-2 ms surrounding the full RF pulse, the ADC samples will be stored in a buffer and made available to the control system on a pulse to pulse basis at 5 Hz. Within this time window, an integrated signal "I" is continuously calculated and compared to a threshold T_i ; exceeding the threshold raises an alarm. Figure 6 is a block diagram concept of the entire loss monitor system.

Due to the time delay of data processing of an alarm signal from an FPGA a fast analog comparator circuit will be needed to provide a fast reaction time to high losses. The alarm signals from the comparator and the FPGA will be OR-ed and the result sent to the MPS. The reaction time to losses is mainly determined by the propagation time of the signal in the cable. The overall length of the ASTA is 133.5 meters so based on expected FPGA processing times (~ 1ns) and cable delays of ~0.4µs it would be reasonable to expect a response time of 1-2 µs from the protection system overall.

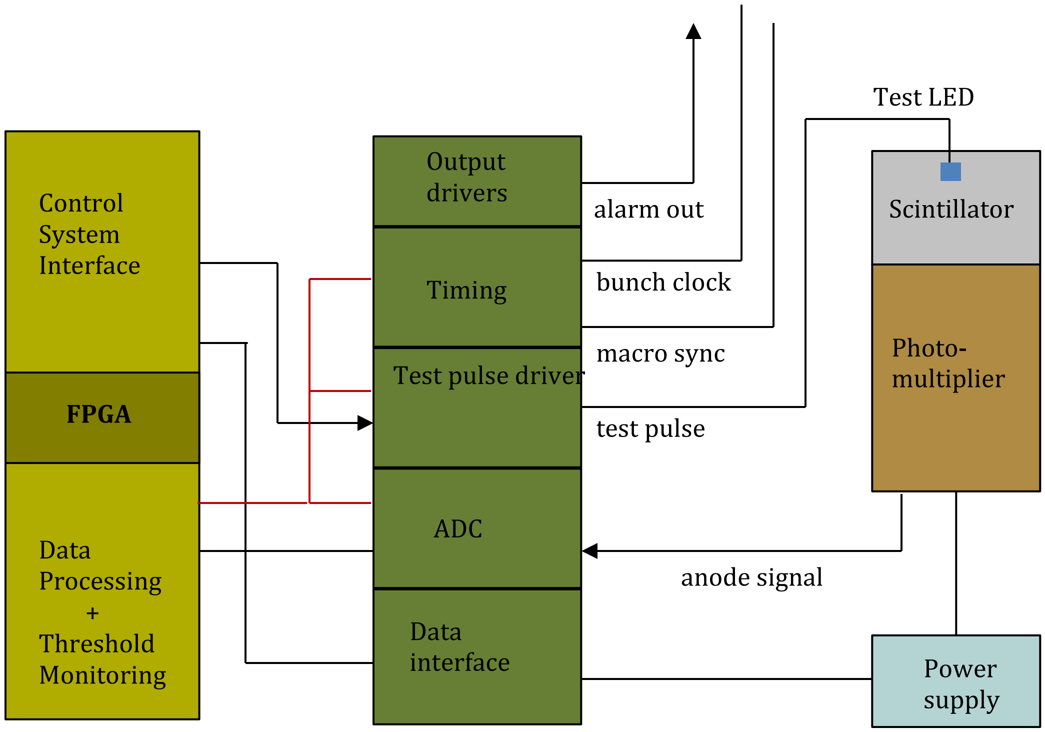

Figure 6. Loss monitor system concept

Cryogenic Loss Monitors

Although loss monitors are typically one of the main diagnostics for protecting the accelerator from beam induces damage. Most accelerator facilities do not cover the cold sections of the machine with loss monitors. To address these issues a Cryogenic Loss Monitor (CLM) ionization chamber capable of operation in the cold sections of a cryomodule has been developed and will be installed and tested [2]. The monitor electronics have been optimized to be sensitive to DC losses and the signals from these devices will be used to study and quantify dark current losses in particular, see figure 4. In order to increase the resolution bandwidth and the response time of the devices a new scheme which uses a Field Programmable Gate Array (FPGA) based Time-to-Digital converter (TDC) method is implemented [3] instead of a standard pulse counting method. This potentially renders these monitors as useful devices for both dark current monitoring and machine protection. These monitors under consideration are custom built detectors. They are an all-metal designed which makes them intrinsically radiation hard and suitable for operation at 5 Kelvin to 350 Kelvin.

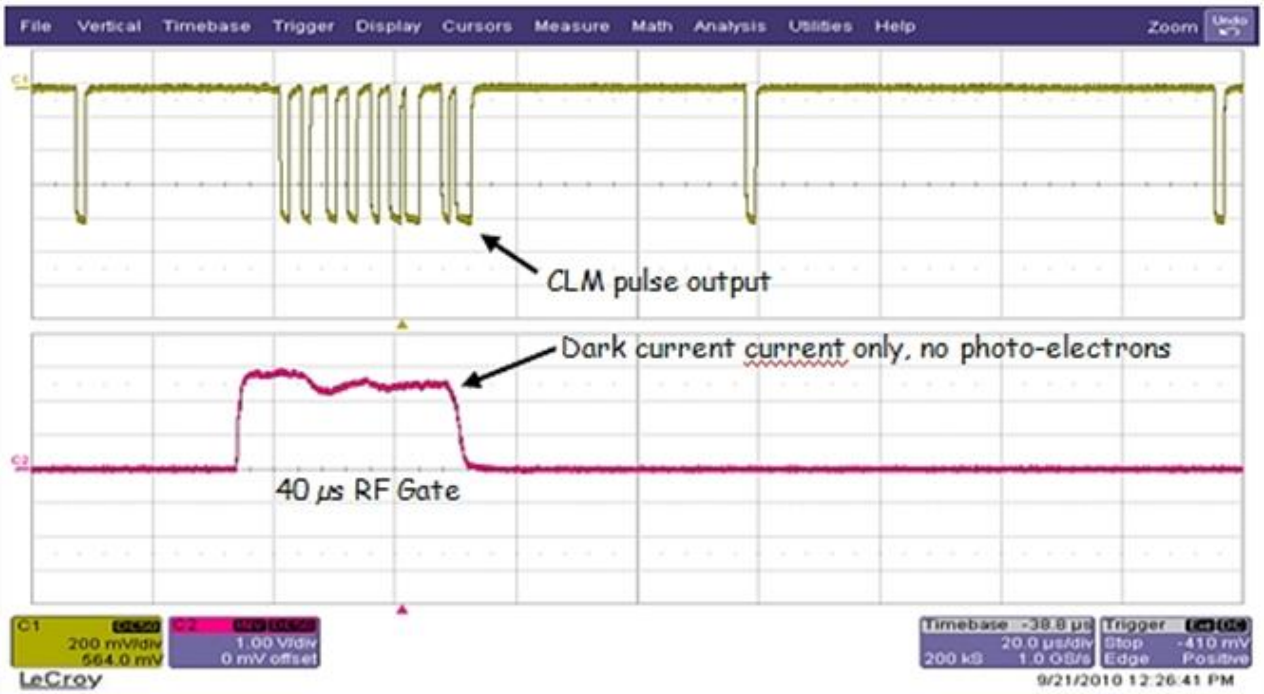

Figure 7. Reaction of CLM to dark current losses in a test beam.

Controls Integration

The MPS will need server support for the various hardware systems to view, configure and diagnose the system. Already there are currently several servers under development for the beam loss monitor system and the laser pulse controller. These servers were implemented using the PowerPC 5500 series boards running VxWorks 6.4 and implementing the ACNET protocol. Some of the main requirements for these servers include:

- Time-stamping at a sub-microsecond resolution in order to allow for data correlation.
- Circular buffers that are logged using ACNET data loggers and thus provide a repository used for post-mortem analysis.

A control system that is well integrated with all MPS components, from the various front-ends to the high level applications, is critical to leveraging the full functionality of that control system.